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**FATIGUE LIFE ASSESSMENT OF
155-MM M776 CANNON TUBES**

**MICHAEL J. AUDINO
JAMES G. BENDICK
JOHN J. KEATING**

**KENNETH D. OLSEN
PAUL M. WEBER
DANIEL J. CORRIGAN**

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**US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050**



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Mr. Daniel Crayon	Material Characterization
Mrs. Allison Welty	Chemical Analysis

INTRODUCTION

Benet Laboratories has the responsibility for safe fatigue life (durability) testing of cannon system components. This safe service life evaluation is accomplished by conducting constant amplitude fatigue testing in a laboratory setting. One such cannon component that requires testing is the gun tube. After each tube has received the required number of live fire rounds necessary to generate initial crack damage at the bore surface as a result of propellant temperature, chemistry, and other contributors (also known as heat-check cracking), it is brought to the laboratory for final hydraulic fatigue testing. International Test Operating Procedure ITOP-3-2-829 (ref 1) dictates armament durability testing and requires that a minimum of six tubes be tested to failure to establish a Final Safe Fatigue Life (FSFL). This report describes the testing conducted in determining the FSFL of the 155-mm XM776 cannon tube. Because the XM776 cannon tube closely approximates the geometric and mechanical features of the 155-mm M284 cannon tube, only two XM776 tubes were tested. Then the data were combined with prior M284 data to establish an FSFL for the XM776 cannon tube.

TEST SPECIMEN DESCRIPTION

A sample size of two prototype 155-mm M776 gun tubes was hydraulically fatigue tested to failure at Benet Laboratories to assist in determining the FSFL for the weapon. The subject tubes were serial numbers (S/N) 001 and 003. The two tubes were manufactured by Watervliet Arsenal and sent to Yuma Proving Ground for initial test firing before being returned to Benet Laboratories for hydraulic fatigue testing. The loading history for each tube is listed in Table 1.

Upon arrival at Benet, a number of test samples were taken from the tubes to verify if enough live fire rounds had been applied. A minimum number of live fire rounds are necessary to generate the required pretest crack damage at the bore surface. With enough conditioning, ample crack depth can be generated where further crack growth becomes a stress-dominated phenomenon easily replicated in a laboratory setting. Additional exposure to the firing environment (heat, propellant gases and by-products, etc.) does not provide further contribution to crack growth at this point. It is important to understand that ample prefatigue conditioning is essential for laboratory cycling to be an effective method in determining safe fatigue life. It is from the small cracks generated during prefatigue conditioning that inside diameter failures typically originate.

Figure 1 illustrates a macroscopic view of a typical bore surface after sufficient live fire rounds have been applied for the commencement of laboratory cycling. The heat-checking, or "dry lake bed" appearance, is apparent. Figure 2 is a transverse section of Figure 1 showing the uniform array of heat checks and the fatigue cracks that grow from heat checks. The heat checking in this photograph ranges from 0.010-inch to 0.020-inch. Figure 3 is a high magnification micrograph of Figure 2. Once again, a fatigue crack emanating from a heat-check location is apparent. Finally, Figure 4 shows how a heat-check crack has initiated a fatigue crack that has penetrated through the chromium plate and into the base metal causing chromium loss

and substrate melting. With acceptable bore damage developed during prelaboratory live firing, laboratory fatigue testing has proven to be equivalent to test firing in propagating this initial damage to failure.

Test specimens were chosen from each tube based on the highest internal pressure, as well as geometric configurations that pose any fatigue concern. As a result, two specimens from each tube were tested. The first, or breech end, specimen from each tube was comprised of the first 52 inches of that tube. The second, or keyway, specimen from each tube was 34.50 inches in length and was cut from the 64.50-inch location (as measured from the rear face of the tube) forward. This section was chosen because of a longitudinal notch configuration cut on the outside diameter of the barrel. Figure 5 illustrates the cutting plan for the tube and clearly shows where the test specimens were taken. The breech end test specimen and the keyway test specimen are detailed in Figures 6 and 7, respectively. Mechanical property and chemical composition data were gathered, in addition to cycles-to-failure data described below. Mechanical and fracture properties were evaluated in the tubes adjacent to the fatigue specimen to validate material conformity. Table 2 lists the tensile test results, while Table 3 lists the fracture toughness and Charpy energy test results. Table 4 provides the residual stress state for the tubes tested, and Table 5 lists the chemical composition of the two tubes.

Once the test specimens were cut to length, sealing pockets were machined into each end to accommodate an aluminum/polymer sealing assembly during testing.

TEST PROCEDURE AND EQUIPMENT

Constant amplitude fatigue testing was conducted on each test section. The breech end specimens were cyclically pressurized from a minimum pressure of 4,800 psi to a peak pressure of 58,800 psi (stress ratio, $R = 0.082$). The notched keyway sections were tested from a minimum pressure of 4,800 psi to a peak pressure of 49,240 psi (stress ratio, $R = 0.097$). These peak pressures are also known as the extreme service condition pressures (ESCP) (ref 1). They represent the highest pressure developed in these sections of the gun tube while firing the top zone charge under the most severe conditions for which the system is designed. The full definition of ESCP is listed in the NATO Standardization Agreement (STANAG 4110) (ref 2). All tests were conducted in the open-ended condition.

Historically, three methods of sealing closure support can be used during the fatigue testing of cannon tubes, namely, the mandrel support method, load-frame support method, or a hybrid mandrel-press support method. The subject tests were conducted using the load-frame support method. This approach uses full cross-section end closures equipped with aluminum/polymer sealing assemblies at each end of the test specimen. In turn, the sealing assemblies were held in place during pressurization by placing the entire test assembly into a large press. The large press prevented the sealing assemblies from exiting the tube section during pressurization. These sealing assemblies consisted of a rubber O-ring, a Buna N (90 durometer) back-up ring, and an aluminum wedge ring in each sealing pocket. The rubber O-ring served as

the initial low-pressure seal and, as the internal pressure was increased, forced the wedge ring against the sealing pocket of the tube. The combination of a well-machined sealing pocket and a snug-fitting wedge ring did not allow the rubber O-ring to extrude past the sealing closure, thus producing an acceptable high-pressure seal. High-pressure fluid was pumped into the test specimen through a small porthole in the upper closure. Figure 8 is a photograph of the test setup including the forward XM776 test section.

A pressure intensifier plumbed to the test specimen pressurized the test fluid within the specimen. This intensifier is a hydraulic actuator with an upper and lower piston head. The 20-inch diameter lower piston is acted upon by standard hydraulic oil pressurized to 3,000 psi. The reduction to the smaller 3-inch diameter upper piston causes intensification in pressure based on the ratio of areas. With respect to fluid compressibility and specimen volume, pressures as high as 120,000 psi can be obtained. The intensifier is capable of displacing approximately 92 cubic inches per stroke although much less displacement was required for our test. The high-pressure fluid used during this test was low viscosity synthetic oil capable of sustaining pressure of approximately 135,000 psi without solidifying. A Precise Corporation pressure transducer connected to a digital indicator monitored pressure. The transducer has an accuracy of ± 0.5 percent at 100 Ksi. A bulk modulus-operated automatic controller controlled pressure. A specimen-mounted strain gauge was also in place to record strain throughout the test.

Inspections were conducted prior to and during testing by employing nondestructive testing techniques to measure crack growth, as well as material defects and flaws. Cracks growing from the bore were measured by ultrasonic inspection. A level II certified inspector using Krautkramer USIP-11 flaw detectors and 5 to 15 MHz probes carried out this inspection. Cracks growing from the outside surface of the tube were identified using magnetic particle inspection. Upon failure each specimen was cut, split, and photographed to reveal the fracture surface.

RESULTS

Table 6 lists results from the two-sample fatigue life test. As the table demonstrates, the weakest portion of the tubes consisted of the breech end specimens with failure cracks emanating from the bore in the charge-notch region of both tubes. Tube S/N 003 failed in a ductile mode with steady crack growth, while Tube S/N 001 experienced an unexpected running crack emanating from the charge notch and continuing to the breech face of the tube. There was no material fragmentation associated with any of the failures. The keyway sections failed from a through-wall crack emanating from the bore and growing to the outside diameter surface at a location approximately 92 inches from the rear face of both tubes.

Figures 9 and 10 show failure locations of the two breech end test sections. Figures 11 and 12 show an enlarged view of the breech end test sections and the failure location. The fracture surface for each breech end test section is shown in Figures 13 and 14. Figures 15 and 16 illustrate the two keyway test sections with the failure location noted. Figures 17 and 18

illustrate an enlarged view of the keyway test sections with the failure location noted. The fracture surface for each keyway test section is shown in Figures 19 and 20.

It is noteworthy to mention that the -40°F Charpy impact energy and the fracture toughness values for these tubes are at the lower end of the acceptable range. These values do not correlate with any accuracy to the upper-shelf correlation of Barsom and Rolfe (ref 3), since this correlation is based on different types of steel. These low Charpy and fracture toughness values are considered to cause the unstable, running crack failure mode of tube S/N 001.

FINAL SAFE FATIGUE LIFE DETERMINATION

The overall fatigue life of each tube is the sum of the laboratory fatigue cycles and any rounds fired at ESCP conditions (Table 6). Rounds fired below ESCP conditions are not considered for the FSFL calculations. The ITOP provides the procedures used in establishing the FSFL. When determining the mechanical final safe fatigue life (as opposed to wear life), the ITOP requires the use of a two-parameter lognormal distribution method (ref 4). Statistical procedures for the lognormal distribution are derived from procedures for the normal distribution. In particular, if we have laboratory fatigue failures x_1, \dots, x_N , then the mean and the standard deviation of the logarithms are calculated as follows:

$$y_i = \ln x_i \text{ for } i = 1, \dots, N$$

$$\text{mean, } m = (1/N) \times (y_1 + \dots + y_N)$$

$$\text{standard deviation, } s = [(1/N - 1) \times [(y_1 - m)^2 + \dots + (y_N - m)^2]]^{1/2}$$

With the mean and the standard deviation of the logarithms known, the FSFL can be calculated using the following formula:

$$\text{mechanical safe service life} = \exp[m - Ks]$$

where K is a tolerance factor (ref 4) dependent only on confidence, reliability, and sample size. The ITOP suggests tolerance factors based on 90 percent confidence and 0.999 reliability. Because the XM776 cannon tube closely approximates the geometric and mechanical features of the 155-mm M284 cannon tube, only two XM776 tubes were tested and the data combined with prior M284 data to establish a fatigue life for the XM776 cannon tube. The Special Projects Branch of Benet Laboratories has the responsibility for making the service life calculation and considers the XM776 data to be basically of the same statistical population as the M284 data with the exception of the "mu" parameter (per Appendix C of ITOP 3-2-829). Even so, it can be said with 90 percent confidence that the fatigue life for the XM776 cannon tube is no less than 3,000 effective full charges. This satisfies the XM776 design requirement of exceeding the M284 wear life of 2,650 effective full charges (M203A1 charge). Determination of the exact FSFL of the XM776 cannon tube will involve the testing of four additional tubes as required by the ITOP.

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1. "International Test Operating Procedure for the Cannon Safety Test," ITOP Report #3-2-829, U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, MD, 1992, p. 4.
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3. Barsom, J.M., and Rolfe, S.T., "Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition-Temperature Range," *Impact Testing of Metals, ASTM STP 466*, American Society for Testing and Materials, Philadelphia, PA, 1970, pp. 281-302.
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5. Audino, M., Underwood, J., Troiano, E., Fajczak, R., and Rickard, C., "Investigation of Early Failure During Laboratory Cycling of 155-mm XM284 Tube, Serial Number 11," ARDEC Technical Report ARCCB-TR-93025, Benet Laboratories, Watervliet, NY, June 1993.

TABLES

Table 1. Pretest Loading Histories

Zone	M230/3	3W	7	7W	8S	Proof	No. of Records	Total Rounds	Total EFC*
S/N 001	0	3	0	12	424	1	72	512	498
S/N 003	23	0	3	33	489	1	0	549	500

* Effective Full Charges

Table 2. Tensile Test Results

Tube S/N	0.2% Yield Strength (Ksi)	0.1% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Elastic Modulus (Mpsi)	Reduction in Area (%)
001	178.6	176.4	190.1	12.8	29.3	37.5
003	177.2	174.7	188.7	12.3	29.3	34.5

Table 3. Fracture Toughness and Charpy Energy Test Results

Tube S/N	Fracture Toughness K _{ij} (RT*) (Ksi√in.)	-40°F Charpy Energy (ft-lbs)
001	117, 117, 120	15, 15, 18
003	108, 112, 124	15, 16, 16

* Room Temperature

Table 4. Residual Stress Test Results

Tube S/N	Measured Overstrain (%)
001	73.3
003	75.8

**Table 5. Chemical Composition Test Results
(Weight Percent)**

Tube S/N	Ni	Cr	Mo	V	Mn	Si	Cu	P	S	C
001	1.759	0.856	0.435	0.117	0.537	0.227	0.096	0.007	0.004	0.320
003	1.810	0.879	0.430	0.120	0.564	0.252	0.102	0.007	0.009	0.339

Table 6. Laboratory Fatigue Test Results

Tube S/N	Test Section	ESCP Rounds	Laboratory Cycles	Total Cycles-to-Failure	Failure Location
001	Breech End	450	7,648	8,098	Charge Notch
	Keyway	450	18,030	18,480	92"RFT @ 6:00
003	Breech End	443	7,194	7,637	Charge Notch
	Keyway	443	17,457	17,900	92"RFT @ 6:00

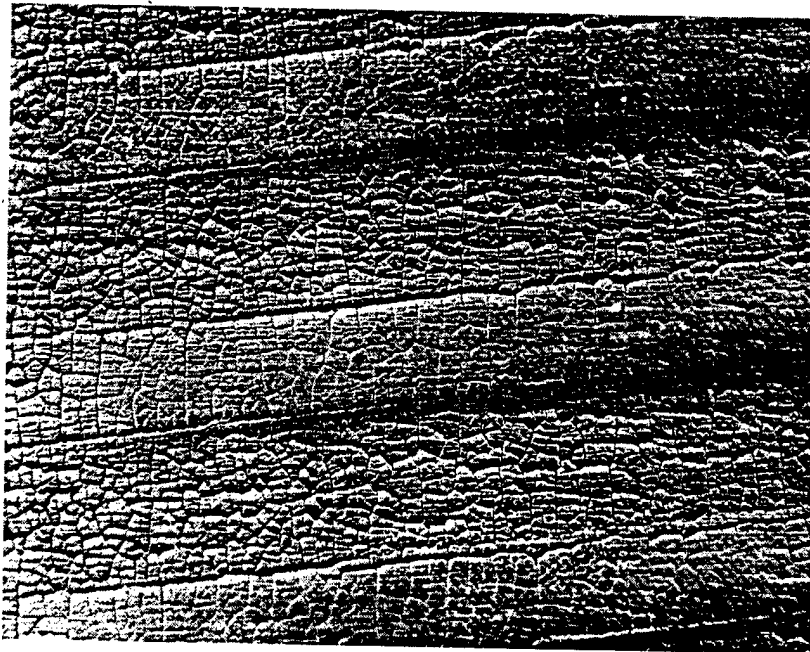


Figure 1. Magnified view of heat checking on the bore surface of a rifled 155-mm cannon tube.

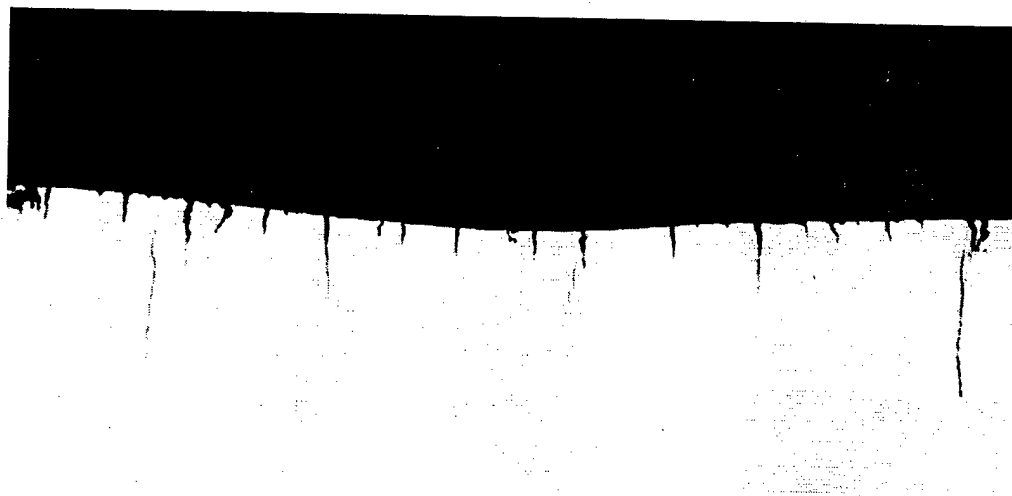


Figure 2. Transverse view of heat-check damage and resulting fatigue cracking.

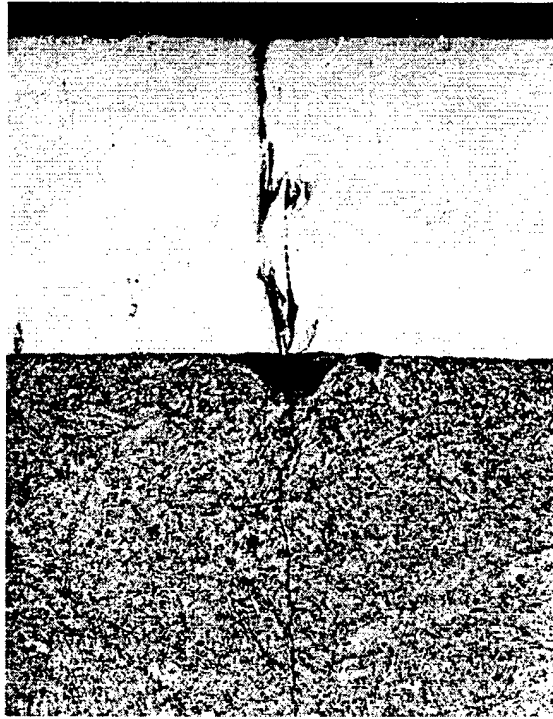


Figure 3. Penetration of cracks through chromium plating and into tube substrate.



Figure 4. Continued fatigue crack growth plus substrate melting and chromium loss.

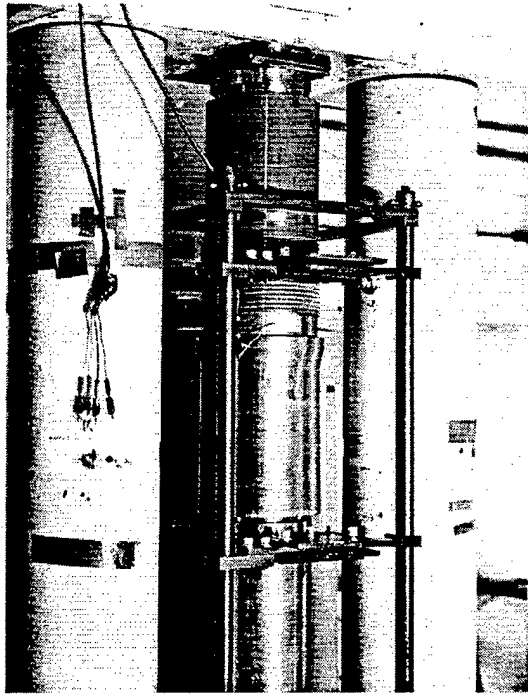


Figure 8. Typical fatigue test setup.

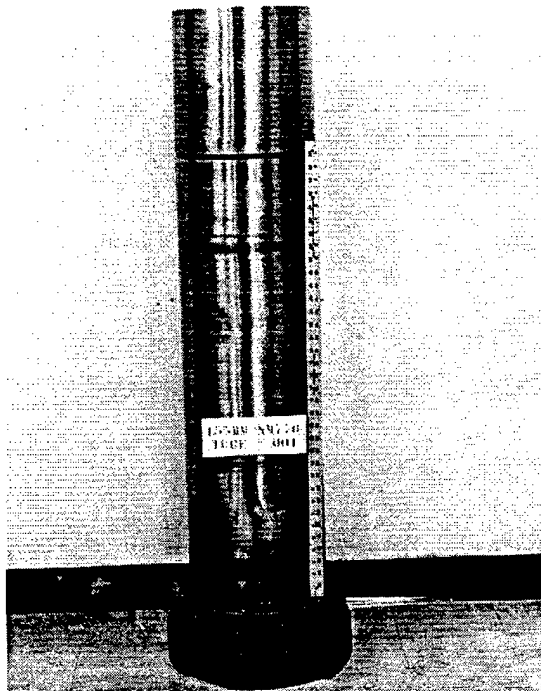


Figure 9. XM776 S/N 001 breech end failure site.

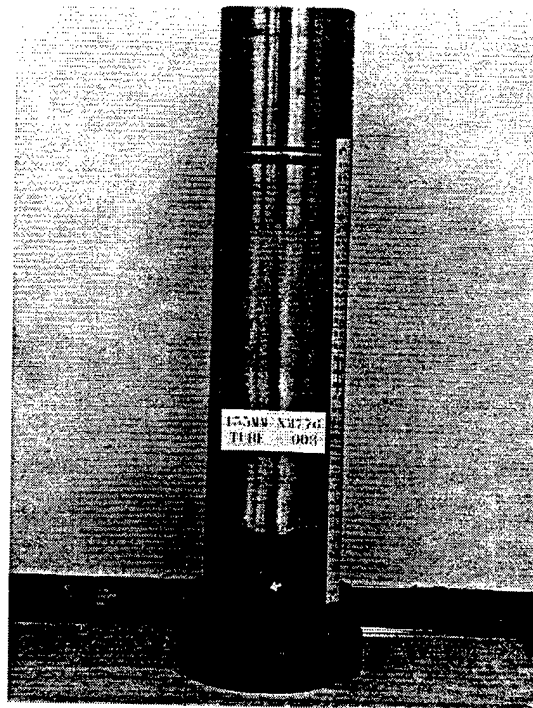


Figure 10. XM776 S/N 003 breech end failure site.

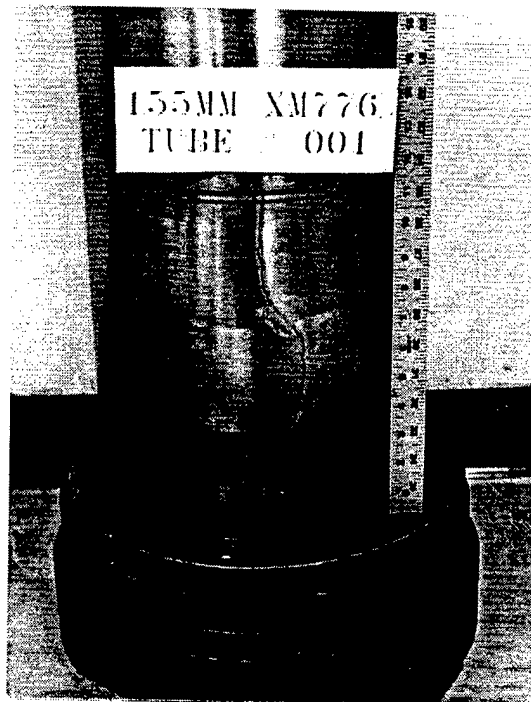


Figure 11. XM776 S/N 001 breech end failure site (enlarged view).

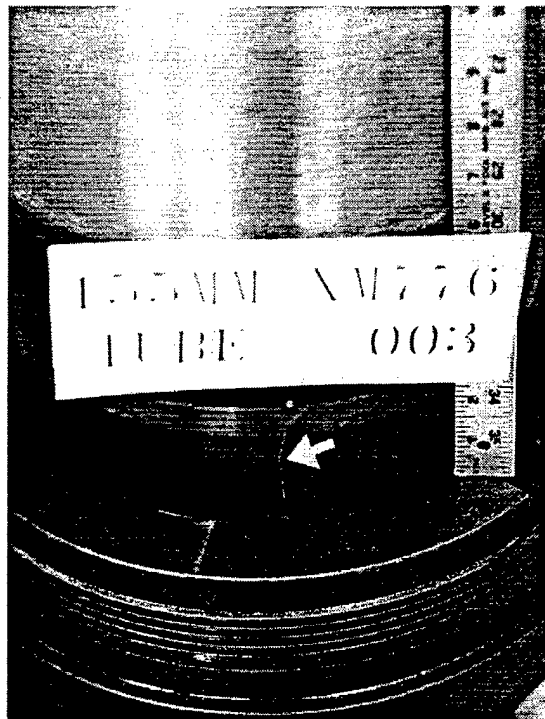


Figure 12. XM776 S/N 003 breech end failure site (enlarged view).



Figure 13. XM776 S/N 001 breech end fracture surface.

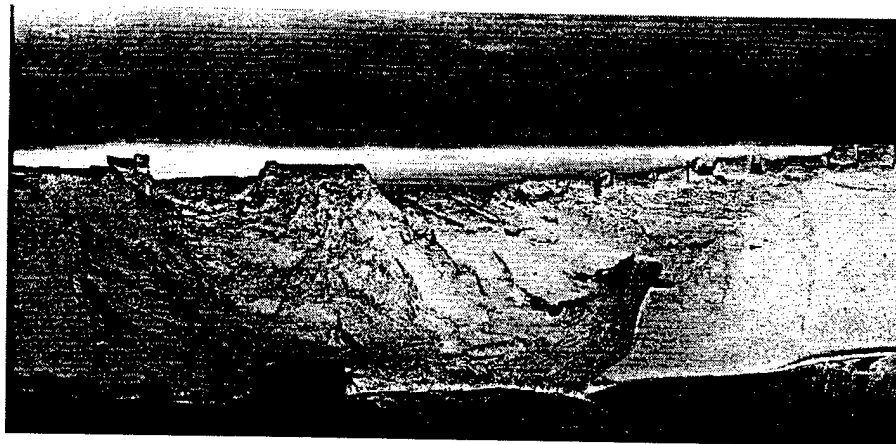


Figure 14. XM776 S/N 003 breech end fracture surface.

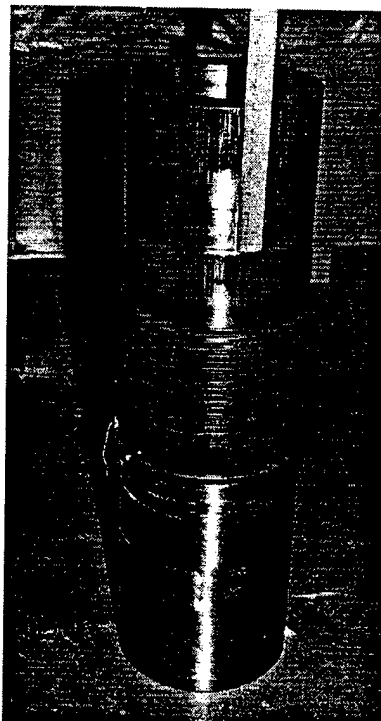


Figure 15. XM776 S/N 001 keyway failure site.

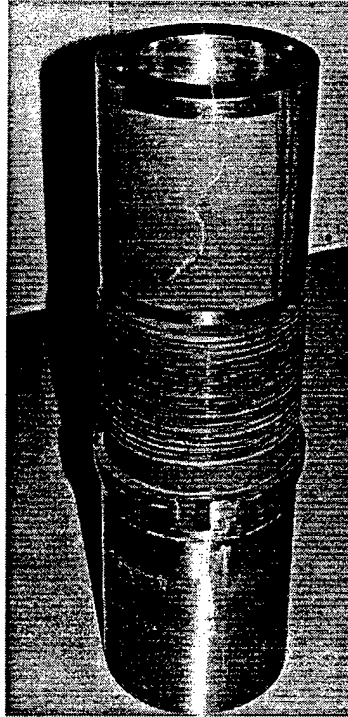


Figure 16. XM776 S/N 003 keyway failure site.

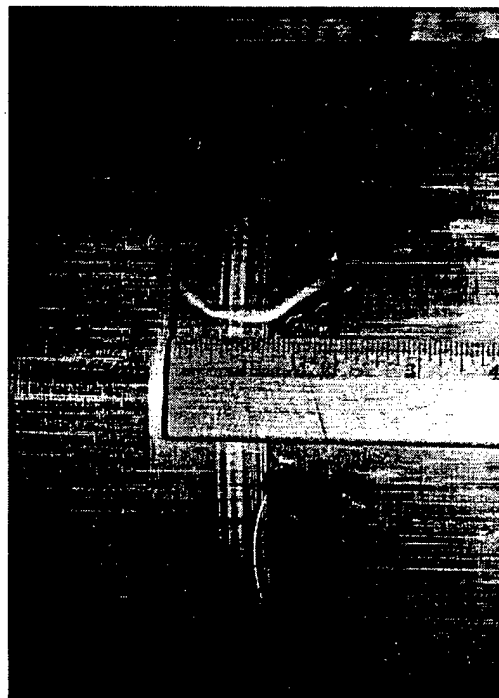


Figure 17. XM776 S/N 001 keyway failure site (enlarged view).

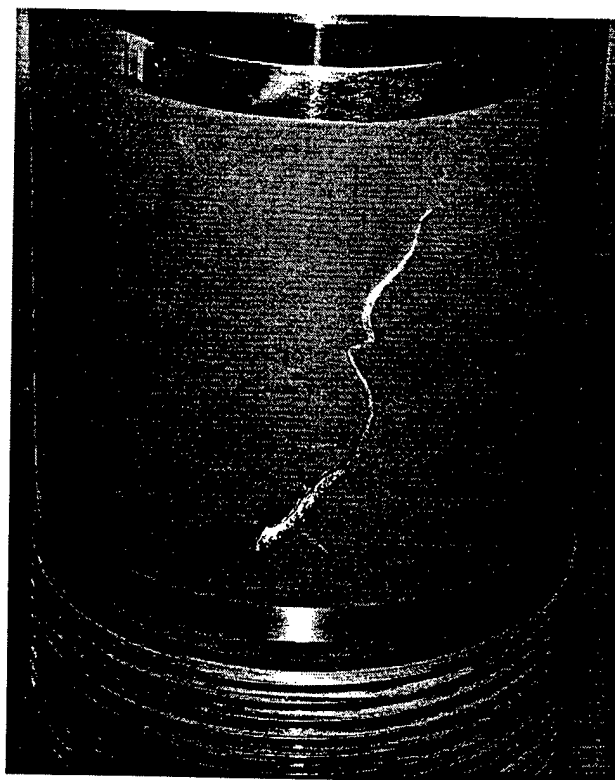


Figure 18. XM776 S/N 003 keyway failure site (enlarged view).

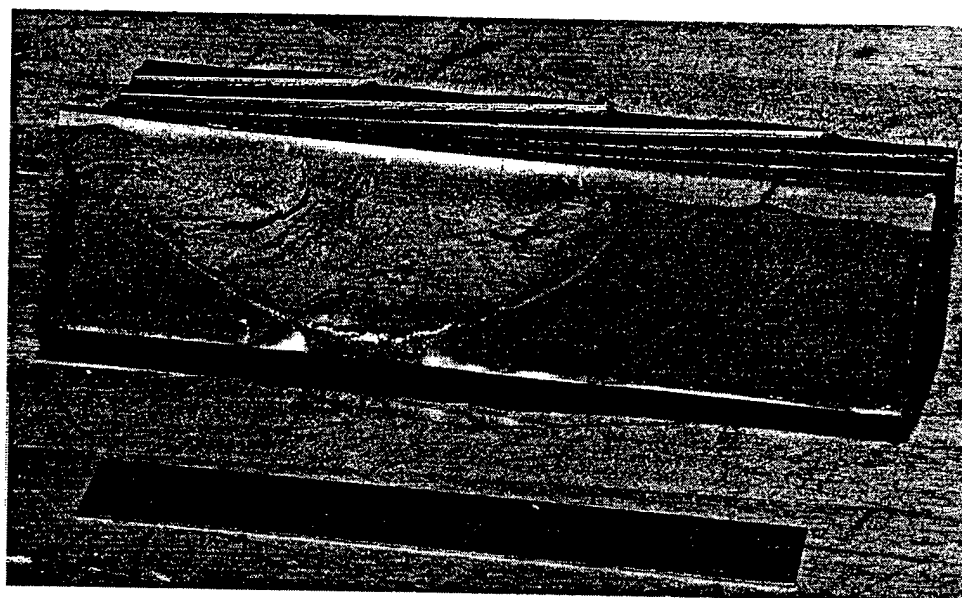


Figure 19. XM776 S/N 001 keyway fracture surface.



**155mm XM776 Lightweight
Tube #003
17,457 Lab Cycles**

Figure 20. XM776 S/N 003 keyway fracture surface.

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